A Low Upper Limit to the Lyman Continuum Emission of two galaxies at $z \simeq 3^1$

E. Giallongo

Osservatorio Astronomico di Roma, via Frascati 33, Monteporzio, I-00040, Italy

S. Cristiani

ECF, European Southern Observatory Karl-Schwarzschild Strasse, Garching bei Munchen, D-85748, Germany

Osservatorio Astronomico di Trieste via G. B. Tiepolo, 11, Trieste I-34131 Italy

S. D'Odorico

European Southern Observatory, Karl-Schwarzschild Strasse, Garching bei Munchen, D-85748, Germany

A. Fontana

Osservatorio Astronomico di Roma, via Frascati 33, Monteporzio, I-00040, Italy

ABSTRACT

Long exposure, long-slit spectra have been obtained in the UV/optical bands for two galaxies at z=2.96 and z=3.32 to investigate the fraction of ionizing UV photons escaping from high redshifts galaxies. The two targets are among the brightest galaxies discovered by Steidel and collaborators and they have different properties in terms of Lyman- α emission and dust reddening. No significant Lyman continuum emission has been detected. The noise level in the spectra implies an upper limit of $f_{rel,esc} \equiv 3f(900)/f(1500) < 16\%$ for the relative escape fraction of ionizing photons, after correction for absorption by the intervening intergalactic medium. This upper limit is 4 times lower than the previous detection derived from a composite spectrum of 29 Lyman break galaxies at $z \simeq 3.4$. If this value is typical of the escape fraction of the $z \sim 3$ galaxies, and is added to the expected contribution of the QSO population, the derived UV background is in good agreement with the one derived by the proximity effect

Subject headings: galaxies: distance and redshifts — galaxies: formation — intergalactic medium

¹Based on observations obtained in service mode at the ESO VLT for the program 65.O-0631

1. Introduction

The integrated ultraviolet background (UVB) arising from quasars and hot, massive stars in star-forming galaxies is likely responsible for maintaining the high degree of ionization of the intergalactic medium (IGM) we observe in the Lyman- α forest lines in the absorption spectra of background QSOs (e.g. Bechtold 1994; Giallongo et al. 1996). Moreover it can affect the processes of galaxy formation and evolution in particular for the less massive systems (e.g. Babul & Rees 1992; Benson et al. 2001).

The contribution of QSOs to the UVB as a function of redshift is the easiest to assess with some degree of reliability based on the estimates of the quasar luminosity function from z = 0 to $z \sim 5$ (e.g. Haardt & Madau 1996).

Hot, massive stars in star-forming galaxies have also been suggested as important contributors to the UVB (Bechtold et al. 1987; Songaila, Cowie, & Lilly 1990; Miralda-Escudé & Ostriker 1990; Bianchi, Cristiani, & Kim 2001) at early epochs. Photometric and spectroscopic data on the galaxy population at $z \geq 3$ are increasing rapidly (Steidel et al. 1996; Lanzetta et al. 1996; Giallongo et al. 1998; Fontana et al. 1999, 2000) and are providing statistical information on the galaxy luminosity and spatial distributions (Steidel et al. 1999, Poli et al. 2001). Intermediate resolution spectroscopy of the brightest fraction of the high redshift galaxies has been effectively used to derive unique information on the physical properties of these stellar systems like the star formation rate, gas dynamics, metallicity, and dust content (e.g. Pettini et al. 1998).

The detection by Tytler et al. (1995) and by Cowie et al. (1995) of CIV in the Lyman- α forest clouds has provided the first evidence of widespread chemical enrichment in the IGM at $z \sim 3$. Madau & Shull (1996) have computed the ionizing stellar radiation flux which accompanies the production of metals at high-z, thus realizing that this may be significant, comparable to the QSO contribution if a fraction $\gtrsim 25\%$ of the UV radiation emitted from stars can escape into the intergalactic space.

As a consequence, the importance of the contribution to the UVB by the galaxy population depends on the ionizing escape fraction of the UV photons which is a poorly known parameter. At low redshifts, Giallongo, Fontana, & Madau 1997 and Shull et al. (1999) have emphasized that the galaxy contribution is already comparable to the QSO contribution for an escape fraction of 5%. This value is consistent with the upper limits derived from the Hopkins Ultraviolet Telescope (HUT) by Leitherer et al (1995) and Hurwitz et al. (1997) and more recently from the Far Ultraviolet Spectroscopic Explorer (FUSE) by Deharveng et al. (2001).

At the intermediate redshifts $z \sim 1$ recent preliminary results by Ferguson (2001) ob-

tained by means of deep HST imaging with the Space Telescope Imaging Spectrograph STIS seem to indicate a slightly higher average upper limit for the UV ratio of the order of $f_{esc} \lesssim 18\%$.

All these attempts made at low-intermediate redshifts have failed so far to derive a statistically significant detection of the UV escape fraction. Steidel, Pettini & Adelberger (SPA) (2001) on the contrary have recently obtained the first significant detection of Lyman limit flux in a sample of $29~z~\simeq~3.40\pm0.09$ Lyman break galaxies (LBGs) using spectra obtained in a multi object spectroscopy configuration devoted to the redshift identification of the high z galaxy sample. The detected Lyman limit flux corresponds to an escape fraction of $f_{esc}=65\%$. A value that is 3.6-13 times higher than previous upper limits.

In the same period we have also started a program to measure the UV escape fraction by means of deep long slit spectra of individual galaxies. This approach avoids possible biases inherent to the procedure of combining spectra of several different galaxies. We report here the results from two galaxies observed at slightly lower redshift ($z \simeq 3-3.3$) with the FORS2 low resolution spectrograph at the ESO Very Large Telescope (VLT) telescope in the spectral range 3500-6500 Å.

2. Observations

Our galaxies are two among the bright end of the Steidel et al. (1996) sample of $z \sim 3$ star forming galaxies observable from Paranal. They are identified as C2 and D6 and have been observed by Pettini et al. (1998) with an infrared spectrograph to compare the Balmer/OII line emission with the UV continuum emission. They are not included in the subsample used by SPA to produce the composite spectrum and measure the UV ionizing fraction. The two galaxies have magnitudes of R=23.55 and R=22.88 and redshifts z=3.319 and z=2.961 for C2 and D6, respectively, and have different properties in terms of Lyman- α emission, UV shape and dust reddening as shown by Pettini et al. (1998).

The galaxies were observed in the period July - August 2000 with the FORS2 instrument at the Kueyen VLT telescope in service mode. The total exposure times were 19429 sec for C2 and 16432 sec for D6. The targets were observed in general at low zenithal distances with low airmass (1.07 and 1.3 for C2 and D6) to minimize atmospheric absorption.

The spectroscopic observations were performed in long slit with the grism 300V+20. The useful wavelength coverage ranges from 3500 Å to about 6500 Å and the spectral resolution is 420. The extraction and calibration of the spectra has been performed using the context LONG in the ESO-MIDAS package.

After the standard bias subtraction and flatfield normalization, the 2D spectra were stacked from the original frames and an optimal extraction was performed. The wavelength calibration in each frame was used to check the stability of the 2D target position before the stacking. We optimized the subtraction procedure of the sky/detector background which is of course the main source of random and systematic errors for the flux calibrated extracted spectra. Because of background variation on several scales on the chip, sky subtraction was optimized differently in the UV and red part of the spectrum. In particular, different regions above and below the target spectrum were selected in the UV and red parts. A linear fit was adopted for the background shape perpendicular to the dispersion direction. The slope of the linear fit was different for the UV and red part of the spectrum.

In this respect, it should be emphasized the advantage for long slit spectra to perform an optimal sky subtraction. Indeed weak fluctuations in emission or absorption perpendicular to the dispersion direction can affect the estimate of the background level. For this reason, wide regions sufficiently far away from the target were selected for the background subtraction. In this way, the weak fluctuations present in these wide regions were easily removed.

The spectrum extraction was performed using an optimal extraction method fitting the spatial profile of the spectrum. The extraction slit was quite short, 7 pixels or 1.4 arcsec, to maximize the signal-to-noise ratio.

Standard flux calibration was performed to provide a relative flux calibration of the spectra. Wavelength calibration was performed applying the dispersion relation without rebinning at any constant wavelength bin size. This procedure keeps unchanged the original pixel noise but produces a slight variation of the wavelength bin along the spectra.

The calibrated spectra were corrected for atmospheric extinction adopting the airmass values previously mentioned. Finally they have been corrected also for interstellar extinction using the E(B-V) values of 0.015 and 0.05 obtained from the NASA/IPAC Extragalactic Database for the galaxies D6 and C2, respectively and adopting the standard Seaton (1979) extinction curve.

The final extracted and calibrated spectra are shown in Fig.1 and Fig.2 (upper panels) with the resulting noise level. Strong SiII1260, OI1303, CII1334, SiIV1398, SiII1526, CIV1548 absorption lines are clearly visible in the spectra and give the same absorption redshifts for the two galaxies as provided by Pettini et al. (1998). Their rest frame equivalent widths are of the order of 3 Å. At the same time, the Lyman- α emissions are different being stronger in D6 with W = 41/(1+z) = 10.5 Å than in C2, W = 14.5/(1+z) = 3.4 Å and correspondingly the UV dust absorption estimated by Pettini et al. (1998) in the two galaxies is stronger in C2 (A₁₅₀₀=1.14) than in D6 (A₁₅₀₀=0.8).

3. Results

It is clear from Fig.1 and Fig.2 (lower panels) that there is no significant emission shortward of the Lyman limit (912 Å) in both galaxies. The average flux is zero and the noise level in the spectra can provide a useful upper limit to the f_{1500}/f_{900} ratio and hence to the UV escape fraction. As in SPA we define a spectral region shortward of the Lyman Limit sufficiently large to have enough statistics but keeping at the same time a low noise level. The selected rest frame region is between 880 and 910 Å.

The pixel-to-pixel noise rms obtained in the selected region is $\sigma(880-910) = 3.3$ (relative flux densities in Hz⁻¹) for the galaxy C2 which corresponds to an average upper limit flux in the region of $f_{900} < 3.3/\sqrt{54pxl} = 0.45$. The corresponding average flux level at 1500 Å is $33 \pm 2.5/\sqrt{21pxl} = 33 \pm 0.6$. The resulting lower limit to the observed f_{1500}/f_{900} ratio is $f_{1500}/f_{900} > 73$ for the galaxy C2.

Similarly for the galaxy D6 the pixel-to-pixel noise rms obtained in the selected region is $\sigma(880-910)=1.1$ corresponding to an average upper limit flux in the region of $f_{900}<1.1/\sqrt{50pxl}=0.16$. The corresponding average flux level nearby 1500 Å rest frame is $11\pm1.5/\sqrt{30pxl}=11\pm0.3$. The resulting lower limit to the observed f_{1500}/f_{900} ratio is $f_{1500}/f_{900}>69$.

The escape fraction defined as the fraction of emitted 900 Å photons that escapes the galaxy without being absorbed is difficult to estimate since it depends on the intrinsic spectral shape of the source and its reddening. A definition of the UV ionizing escape fraction f_{esc} related to the actual measure is represented by the ratio f_{1500}/f_{900} related to the 1500 Å escape fraction by SPA to avoid any dependence on uncertain parameters like dust reddening. Specifically we adopt a relative escape fraction $f_{rel,esc} \equiv 3 \times f_{900}/f_{1500}$ where the factor 3 is the f_{1500}/f_{900} ratio expected from the stellar synthesis models (cf. SPA). The uncertainties on this predicted value depend on the adopted initial mass function and stellar ages and ranges from about 2.5 to 5.5. We adopt the same factor 3 used by SPA for comparison.

To use the observed f_{1500}/f_{900} ratios for the estimate of the relative UV escape fraction, a correction should be made to take into account for the opacity present shortward of the Lyman- α and in particular in the Lyman continuum region. This opacity is due to the intervening neutral hydrogen not directly associated with the galaxies, the so called intergalactic medium (IGM). This correction is negligible at low redshifts z < 0.1 but becomes important at $z \sim 3$ and should be taken into account. It is clear that a careful correction for intervening absorption in individual objects requires high resolution spectra. In our case we adopt the same correction estimated by SPA in an empirically way using a composite QSO spectrum with a mean redshift of $z \simeq 3.47$. From this composite spectrum the decrement due to

intervening HI absorption has been estimated to be $f_{1500}/f_{900} = 3.85$. Since our galaxies have redshifts not far from that of the QSO composite spectrum, we have adopted the same correction factor.

The resulting 1σ upper limit to the relative UV ionizing escape fraction in both galaxies at z = 3 - 3.3 is $f_{rel,esc} \equiv 3 \times 3.85 \times f_{900}/f_{1500} < 16\%$.

4. Discussion

Steidel and collaborators have provided the first significant detection in a sample of $z \simeq 3.4$ Lyman break galaxies (LBGs). They have used a composite spetrum made by 29 LBGs spectra obtained from the Low Resolution Imaging Spectrometer at the Keck telescope. For the average sample they derive an observed ratio $f_{1500}/f_{900} = 17.7 \pm 3.8$. In Fig.1 and Fig.2 (lower panels) the expected ratio derived by SPA corresponds to the thick horizontal line shown between 880 and 910 Å. The smoothed versions of the spectra to the instrumental resolution are also shown as thick curves only for illustrative purposes. The smoothed spectra fluctuate around the zero flux level shortward of 910 Å and the resulting upper limit on the relative escape fraction, $f_{rel,esc} \lesssim 16\%$, is 4 times lower than the $f_{rel,esc} = 65\%$ SPA detection.

This result can also be compared with other measures derived for individual galaxies at lower redshifts. At z < 0.1 the most recent result has been obtained by Deharveng et al. (2001) for the nearby galaxy Mrk 54 using the Far Ultraviolet Spectroscopic Explorer (FUSE). No flux was detected shortward of 910 Å and the lower limit to the ratio of f_{1500}/f_{900} , as measured from the noise level, was 108 (converting their fluxes in erg/s/cm²/Hz) without correction for intervening IGM absorption). This can be translated in an upper limit to the relative UV escape fraction of $f_{rel,esc} \lesssim 3\%$ (this value is different from the one reported by the authors because of their different definition of the escape fraction which depends on the flux emitted in the H α line). Other 4 f_{1500}/f_{900} ratios reported in their paper from previous observations with the Hopkins Ultraviolet Telescope (Leitherer et al. 1995) give average upper limits in the range $f_{rel,esc} \lesssim 20-30\%$ (with no correction for intervening IGM absorption).

At the intermediate redshifts $z \sim 1$ recent preliminary results by Ferguson (2001) obtained by means of deep HST imaging with the *Space Telescope Imaging Spectrograph (STIS)* seem to indicate a slightly higher average upper limit for the UV ratio of the order of $f_{1500}/f_{900} \sim 17$ corresponding to a relative escape fraction of $f_{rel,esc} \lesssim 18\%$ (preliminary estimate including intervening IGM absorption).

Our upper limits derived from the individual spectra of two galaxies at z = 3 - 3.3 are

more similar to the limits derived from HUT, FUSE and HST at lower redshifts than to the detection by SPA using a composite Keck spectrum of galaxies at $z \sim 3.4$.

In an attempt to understand the difference between the result by SPA and our result, we note the following. The upper limit for the two galaxies we observed are very close in value, although the two galaxies have different properties in terms of Lyman- α emissions and dust reddening. On the other hand it is clear that the Lyman- α emissions of our galaxies $(W=3,11\ \text{Å}$ for C2, D6 respectively) are lower than the average Lyman- α emission in the SPA composite spectrum $(W\sim20\ \text{Å})$. In fact, the $z\simeq3$ galaxy sample used by Shapley et al. (2001) to estimate the optical luminosity function shows a median Lyman- α equivalent width of 0. This implies that about half of the sample shows Lyman- α in absorption and half shows Lyman- α in emission. The Lyman- α equivalent widths of our two galaxies are close to the typical W of the spectroscopic galaxy sample at $z\sim3$. Thus, it is possible that significant UV ionizing photons can escape only the fraction of the $z\sim3$ galaxy population with strong Lyman- α emission. To test this hypothesis it could be interesting to compare the escape fraction for the strong Lyman- α emitters to that for the galaxies with Lyman- α in absorption in the SPA sample.

If this hypothesis were correct it would imply that the average escape fraction of ionizing UV photons present at $z \sim 3-3.5$ could be smaller than previously thought. The consequences of this for the estimate of the UVB produced by the high z star forming galaxies can be evaluated adopting as a reference value our upper limit of $f_{rel,esc} \lesssim 16\%$. At $z \sim 3$ the galaxy contribution has been recently evaluated by SPA who adopted their estimate of the 1500 Å galaxy luminosity function and their derived escape fraction of 65%. Their resulting UVB intensity from the galaxy population alone is $J = 1.2 \times 10^{-21} \text{ ergs s}^{-1} \text{ cm}^{-2}$ $\mathrm{Hz^{-1}\ sr^{-1}}$ which is already larger than the value estimated by the "proximity effect" in the Lyman- α forest of QSO absorption spectra, $J = 5 - 7 \times 10^{-22} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ (see e.g. Giallongo et al. 1996; Scott et al. 2000). The addition of the contribution by the QSO population would increase this discrepancy. To alleviate the problem they argued about a possible overestimate of the QSO contribution to the UVB. Bianchi et al. (2001) used the observed UV star formation history and three different values for the intrinsic f_{1500}/f_{900} ratio, namely 5.3, 21, 42 corresponding to $f_{rel,esc} = 57, 14, 7\%$, respectively, (following the definition of $f_{rel,esc}$ adopted in the present paper) to compare the contribution of the two populations to the UVB and the effects on the evolution of the Lyman- α forest. It is found that, to avoid an overprediction of the total (QSO+galaxies) UVB respect to the value derived from the "proximity effect", the relative escape fraction should be of the order of or smaller than 15%. In this respect our upper limit supports a scenario where the total UVB is consistent with the "proximity effect" at $z\sim3$ with a galaxy contribution of $J\lesssim6\times10^{-22}$ ${\rm ergs~s^{-1}~cm^{-2}~Hz^{-1}~sr^{-1}}$, i.e. no more than a factor 2.5 higher than the QSO contribution.

An UVB produced by this mixed population could account for the metal enrichment of the IGM and for the SiIV/CIV metal-line ratios observed in high resolution QSO absorption spectra (see e.g. Giroux & Shull 1997).

In summary, many pieces of evidence, from the limits derived at lower and intermediate redshifts to the upper limit of $f_{rel,esc} \lesssim 16\%$ presented in the present paper, point toward a lower ionizing escape fraction. We emphasize that our result, however robust, is based on the observations of two $z\sim 3$ galaxies only. A large statistical sample is needed to confirm its implication on the UV background evolution. This is within the grasp of the current instrumentation at very large telescopes.

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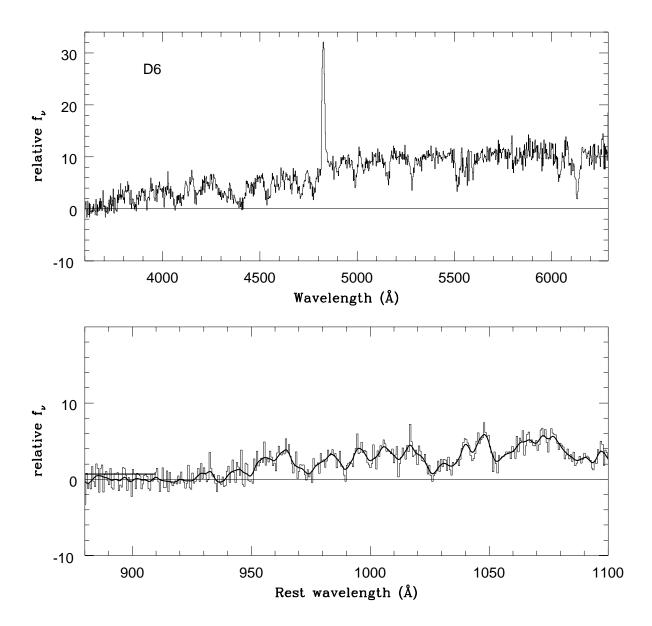


Fig. 1.— The spectrum of the galaxy D6 is shown as a function of the observed (upper panel) and the rest frame (lower panel) wavelengths. The thick curve in the lower panel is the smoothed version to the instrumental resolution. The thick horizontal line from 880 and 910 Å is the predicted Steidel et al. level in the spectrum.

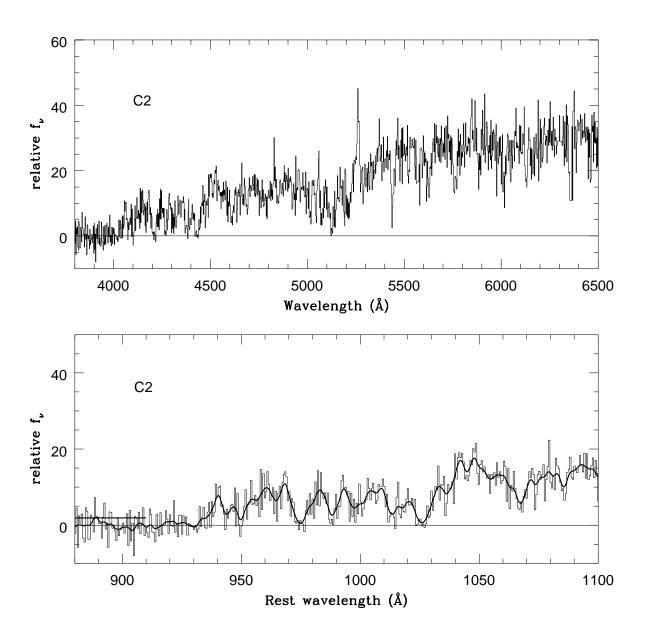


Fig. 2.— The spectrum of the galaxy C2 is shown as in Fig.1.